ELSEVIER

Ecological Engineering 8 (1997) 93–116

ECOLOGICAL ENGINEERING

Rehabilitation of warmwater stream ecosystems following channel incision

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Received 7 August 1996; received in revised form 11 December 1996; accepted 12 December 1996

Abstract

Presented is a case study of two streams (watershed size, 12 and 14 km^2) damaged by channel straightening and incision. One stream was stabilized using a metal sheet piling weir and dormant willow post planting, while the other was treated with a stone weir, stone toe bank protection and willow sprout planting. Fishes and their physical habitats were monitored for 1–2 years before construction and two to three years afterward. Willow planting was not successful, so canopy, bank vegetation, and woody debris density were unchanged. Pool habitat area increased from less than 5% to more than 30% of the total aquatic area. Fish species richness and diversity were unchanged, but species composition shifted away from patterns typical of shallow, sandy runs toward pool-dwelling types, becoming more similar to a nearby lightly-degraded reference site. Median lengths of selected centrarchids increased following rehabilitation. Physical and biological response were more persistent for the stream treated with the stone weir and bank toe protection, possibly because the stone toe produced a more uniform longitudinal distribution of cover and pool habitats than the single weir.

Keywords: Stream restoration; Fish; Physical habitat; Channel incision; Erosion; Streambank protection; Channelization; Sediment

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1. Introduction

Historically, watershed and channel management practices have emphasized conveyance functions and have frequently accelerated channel erosion (Brookes, 1988). Channel bed degradation, a particularly widespread and pernicious type of channel erosion, is characterized by bed lowering that often leads to bank collapse, resulting in channel enlargement (Galay, 1983) and deterioration of stream corridor habitats. For example, straightened, incised streams draining agricultural watersheds in Mississippi are deficient in pool habitats, stable bed material, woody debris and woody riparian vegetation (Shields et al., 1994). Because of the efficiency of straightened, enlarged channels and the lack of floodplain storage for floodwaters, flood peaks tend to be sharper in these incised channels than for non-incised channels and ecologically important exchanges of nutrients and carbon with the floodplain occur rarely or not at all (Shields and Cooper, 1994). Channel incision has occurred in urban and rural settings throughout much of the USA.

Interest in restoring rivers and streams is increasing as the public seeks to regain amenities and resource values afforded by less perturbed systems and ecologists experiment with hydrological restoration of river–floodplain systems to learn more about natural structure and function (Bayley, 1995). Engineers are often called upon to produce designs for these restoration projects. While 'restoration' implies "return of an ecosystem to a close approximation of its condition prior to disturbance" (National Research Council, 1992), 'rehabilitation' as used herein denotes partial return to a pre-disturbance structure or function. Stream ecosystems throughout much of the Midwest and Southeast have been so degraded and the topography and hydrology of their watersheds so transformed that true restoration is not a viable goal (Rhoads and Herricks, 1996).

However, rehabilitation of habitat values, providing some of the ecosystem functions that formerly existed in stream corridors, may be feasible with cost-effective design.

Scientific studies of warmwater stream restoration and rehabilitation projects are scarce (Osborne et al., 1993; Lyons and Courtney, 1990). This paper reports on rehabilitation of deeply incised, low-order warmwater streams draining agricultural watersheds. Effects of two rehabilitation projects on channel stability and on fish and their habitats are assessed based on 5 years of observation. Effects are compared with published results of two other stream corridor rehabilitation projects in nearby, similar watersheds to evaluate the relative magnitude of physical and biological responses.

2. Study sites

Three streams were selected for study (Fig. 1). Two were straightened, incised streams which were treated with stabilization structures and planted woody vegetation during the course of the study. The third was a moderately disturbed, non-incised meandering stream monitored to provide a point of reference (Hughes

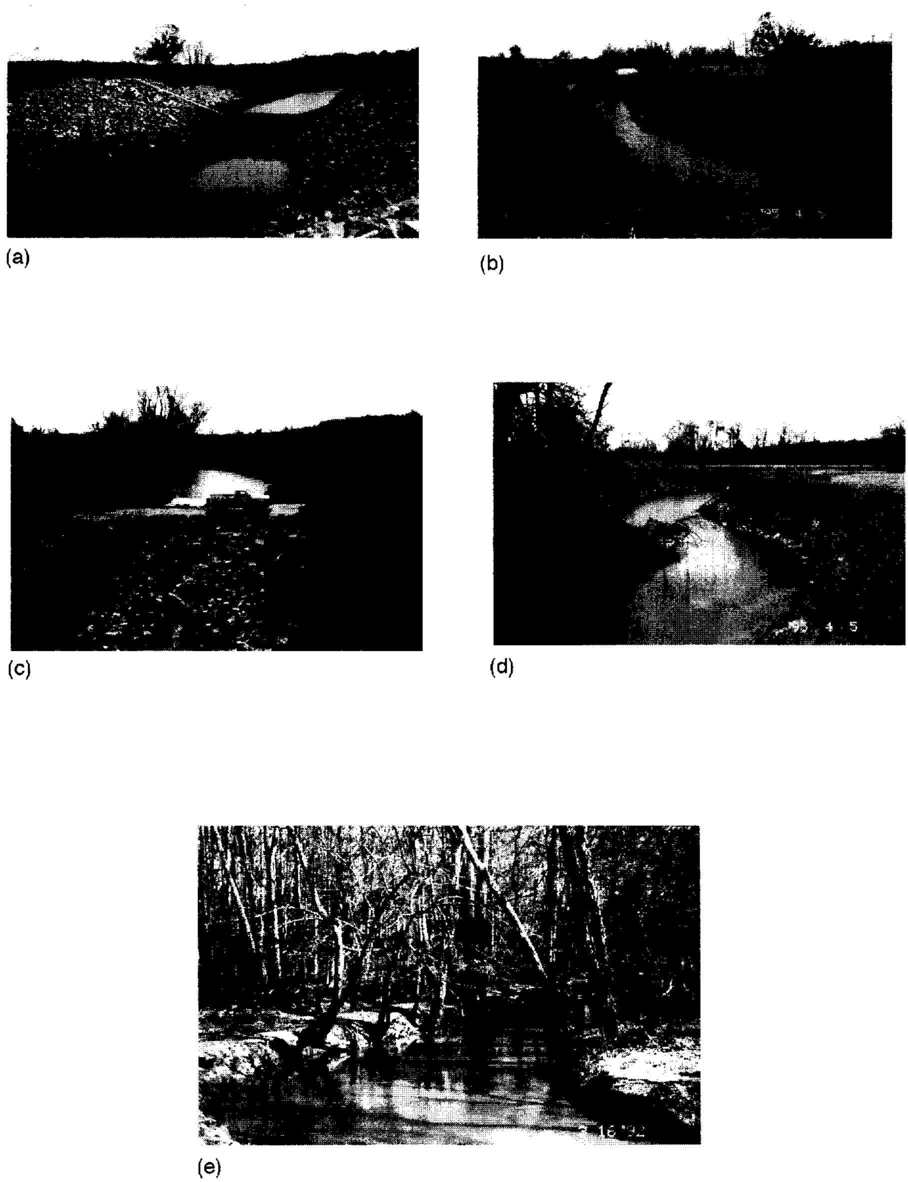

Fig. 1. Study sites in Northwestern Mississippi, USA: (a) MDC, showing sheet pile weir; (b) MDC, showing willow posts shortly after planting; (c) MDC showing stone weir; (d) MDT showing stone toe bank toe protection; and (e) TT-reference stream.

et al., 1986). In this study, the term 'reference' was used to designate a site used to gage the physical and biological potential for damaged stream rehabilitation, not as a scientific control. Although the reference site had a larger watershed (three times greater than the treated sites) and greater baseflow (approximately ten times the treated sites), it contained habitats and fishes typical of low-order streams in this region that have not been subjected to channel incision. Since reference sites vary due to the dynamic nature of climate, hydrology, and man's activities, we sampled the reference site throughout the study using the same protocol as for the treated streams.

Martin Dale Creek (MDC) and Martin Dale Tributary (MDT) were incised streams draining adjacent watersheds of 12.3 and 13.6 km^2, respectively, in the upper Yazoo River basin in northwest Mississippi. Watersheds of these streams are located in the East Gulf Coastal Plain physiographic Province along the bluffline of the Mississippi River Valley. In all three watersheds, soils, topography and land use were typical of many streams along the eastern side of the lower Mississippi River floodplain. Ridges were capped with loess deposits, and valleys were filled with alluvium derived from post-European settlement (ca. 1840–1880) erosion overlying a complex of six or more stratigraphic units, all of which are erodible (Grissinger et al., 1982). Chronology and nature of valley-fill deposits have been described by Grissinger and Murphey (1982, 1986).

Watershed geological conditions were characterized by deep (up to 6 m) loess deposits overlying sand and clay (Simons et al., 1987). No bedrock was exposed and the only geologic controls along channels were outcrops of consolidated clay or cemented sand. During this study, valley bottoms (silt loams) were cultivated for cotton and soybeans, while hillslopes (silty and sandy soils) were wooded or in pasture. Both channels were nearly straight, with depths of about 5 m and top widths of about 20 m and resembled stage II of the conceptual model of incised channel evolution presented by Schumm et al. (1984). Stage II channels are relatively narrow and deep because they are undergoing deepening but little widening. In the model, they are located downstream of primary nickpoints (waterfalls or extremely steep reaches that rapidly erode upstream). One-dimensional flow modeling suggested that the channel capacity of MDC exceeded the 100-year flow (Simons et al., 1987). Bed material was sand with outcrops of hard clay. Along both channels, left banks were nearly vertical, but right banks were benched. Thalweg slopes ranged from 0.002 to 0.003. At base flow (5–60 l s^{-1}), water surface widths ranged from about 1 to 7 m and median depths were usually less than 10 cm. Woody bank vegetation was scarce, except along the lower reaches of MDT where some large trees were growing on top of the banks. The exotic vine, kudzu (*Pueraria lobata*) covered the banks of both channels. Woody debris was scarce, but a few beaver dams would appear in later summer and fall after prolonged low flow and disappear following high flows.

Streams MDC and MDT were stabilized using different treatments (Fig. 2). Structural measures were designed without regard for habitat; however, the projects did include revegetation of banks using willow cuttings. A metal sheet piling weir with a stone-protected approach channel and stifling basin ('drop structure', Little

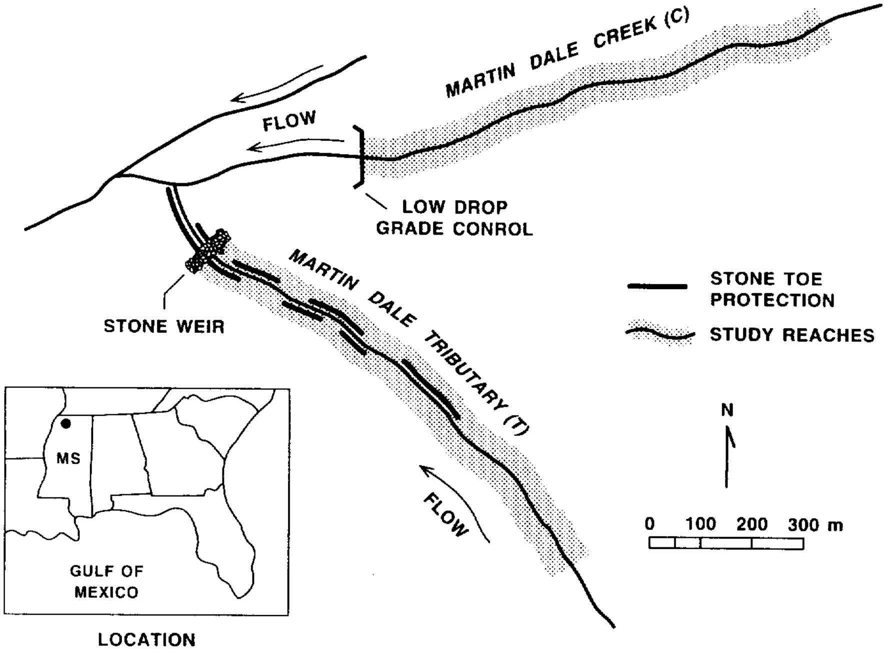

Fig. 2. Location of study reaches showing rehabilitation measures.

and Murphey, 1982) was constructed on MDC. A stone weir was placed in MDT, and a ridge of stone was placed along the toe of a total of 700 m of concave banks upstream of the weir. The drop structure and stone weir created pools upstream that were up to 1 m deep. Downstream of the stone weir in MDT, dumped construction rubble (broken concrete, etc.) created an approximate 10% slope instead of a scour hole. About 3000 willow sprouts (cuttings with diameter less than 1 cm manually thrust 30–36 cm into soil) were planted landward of the stone toe along MDT, while 4282 dormant willow posts 1.5 m long × 8–30 cm diameter were planted 1.2 m deep in both banks along 500 m of MDC immediately upstream of the drop structure. Dormant posts were planted in the face and along the toe of steep, slowly eroding banks (Fig. 1(b)) by making holes using a metal ram mounted on an hydraulic hoe. Posts were planted upright the same day they were harvested. Construction dates were August 1992 through February 1993 and June through August 1991 for MDC and MDT, respectively. Willow sprouts planted along MDT were planted in summer, while posts planted along MDC were planted in February. Costs for rehabilitation measures were about US$196 000 and US$165 000 for MDC and MDT, respectively, in 1991–1992 (personal communication, Mr Phil Haskins, US Army Corps of Engineers, Vicksburg, MS).

The non-incised reference site, Toby Tubby Creek (TT), was located approximately 25 km from MDC and MDT. TT is a sand-bed stream draining a watershed of about 38 km^2. Watershed land use was 12% urban, 22% pasture, 15% crops and

48% forest. Although the main channel had a sinuosity of 1.25, most tributaries were straightened several decades ago. The channel through the study reach and for about 5 km upstream was flanked by a 600 m wide band of forested wetlands (US Soil Conservation Service, 1993). The study reach channel was about 10 m wide and 2 m deep and thalweg slope was about 0.002. During the summer much of the channel was covered by tree canopy, and large woody debris formations were common year-around. Beaver dams and associated ponds were common on the floodplain within this wetland corridor and were occasionally found within the main channel. Evidence of frequent overbank flow (trashlines, sediment deposits, etc.) was common within the wetland corridor, but flooding was not extensive enough to hinder land use outside the wetland corridor. Baseflow discharge during this study ranged from 300 to 500 l s^{-1}.

3. Methods

Effects of rehabilitation on channel boundaries were quantified by surveying channel thalwegs and cross-sections of each stream during 1991–92 and again in 1995. Bed sediments were grab-sampled at the center and quarterpoints of 12 transects across the baseflow channel of each stream (no. of samples per stream = $3 \times 12 = 36$) during 1991 and again in 1993. Physical habitat data were measured semiannually (spring and fall) for 5 years using methods similar to those prescribed by Simonson et al. (1994). Once each spring and once each fall, depth and velocity were measured at regular distance intervals along a minimum of 20 transects distributed along each study reach. Measurements were made at a minimum of 90 points per stream. Depth was measured using a wading rod and velocity was measured at 0.6 times the depth below the water surface using an electromagnetic flow meter. Water surface width was measured using a tape at each transect and at each point where depth and velocity were measured, surficial bed material was visually classified as sand, clay, gravel, etc. Counts of living and dead willow posts were made one year after planting. Survival of willow sprouts was assessed visually.

Fish were collected in spring and fall concurrently with physical data using a backpack-mounted electroshocker. Four 100-m stream subreaches within each 1 km study reach were fished for 6–9 min (mean, 433 s; S.D., 203 s) of electric field application. Fishes longer than about 15 cm were identified, measured for total length and released. Smaller fish, and fish that could not be identified in the field were preserved in 10% formalin solution and transported to the laboratory for identification and measurement. Water temperature, pH, dissolved oxygen and conductivity were measured at midday (between 1000 and 1500 h) on dates when fish were sampled.

Data were examined using basic graphical and statistical procedures. Patterns of fish species abundance were examined by plotting rank-abundance graphs (Magurran, 1988) and recruitment patterns for selected species were examined using successive length–frequency distribution plots. Although construction of rehabilitation structures was completed on MDT in 1991, preliminary analyses of the physical and biological data indicated that response to rehabilitation was gradual rather than sudden. Thus, for statistical analysis, we designated the period 1991–1992 as pre-rehabilitation and the period 1993–1995 as post-rehabilitation for both streams. This approach may have led to more conservative findings regarding the response of MDT to rehabilitation.

4. Results

4.1. Water quantity and quality

Nine of ten measured baseflows in MDT were greater (1.05–32 times) than those in MDC. Discharges in MDT ranged from 25 to 63 l s^{-1}, while those in MDC were only 2–59 l s^{-1}. The average of the baseflows measured during the first year of the study (1991) was about three times greater than the average of the 1992–1995 values, reflecting a wet period in the first half of 1991 when precipitation was about 200% of normal (normal $\sim$ 1400 mm $year^{-1}$ for all three sites) (National Climatic Data Center, 1995, 1996). Water quality data from all three streams indicated conditions were suitable for aquatic life. Mean temperature of stream MDC was 2°C warmer than for stream MDT ($p = 0.02$, paired t-test). TT water quality data fell within the same range as those from MDC and MDT, but temperature, dissolved oxygen and specific conductance were generally slightly lower in TT. The difference in base flows and temperatures for MDC and MDT reflects greater groundwater inflows to MDT, where artesian inflows ('sand boils') were often observed in the bed. Aquicludes underlying many northwest Mississippi watersheds are not conformable with surface topography, leading to groundwater transfer and widely varying baseflows between adjacent watersheds (Grissinger et al., 1982). The similarity of the geometry of the two channels confirms that channel shape and size are defined by geomorphic and hydraulic factors independent of groundwater contributions.

4.2. Channel morphology

Stream channels were horizontally stable during the periods between channel surveys, and average values of channel width and depth changed little. However, MDC and MDT thalweg profiles were dynamic, with up to 1 m of aggradation occurring upstream of the MDC drop structure during the 3 years between the surveys (Fig. 3). Comparison of the 1995 MDC survey and one obtained by Simons et al. (1987) in 1985 revealed that average slope was reduced from 0.0027 to 0.0021 by deposition above the drop structure and erosion further upstream. Aggradation upstream of the stone weir on MDT also extended about 400 m upstream, but was less uniform, ranging from 0 to 60 cm. In the aggraded reach, thalweg slope was reduced from about 0.002 to about 0.001, but no change was observed in thalweg elevations or slope upstream of the aggraded reach. About 50–90 cm of deposition occurred at three locations along the TT thalweg, but general aggradation did not (Fig. 3).

Median bed material size in MDC and MDT ranged from about 0.1 to 0.8 mm, and hard clay outcrops were common. Gravel was absent except for a few pockets trapped on the downstream face of the MDT weir (Fig. 1(c)). Median bed material size in all streams became slightly finer following rehabilitation. Fine sediments were retained upstream from the weirs on MDC and MDT and in smaller zones of reduced velocity. Material finer than sand (aside from consolidated clay outcrops) was virtually absent prior to construction, but comprised an average of 8 and 10% of bed sediments in MDC and MDT, respectively, following construction and ranged as high as 67%. The percentage of fine sediment in the bed of TT increased

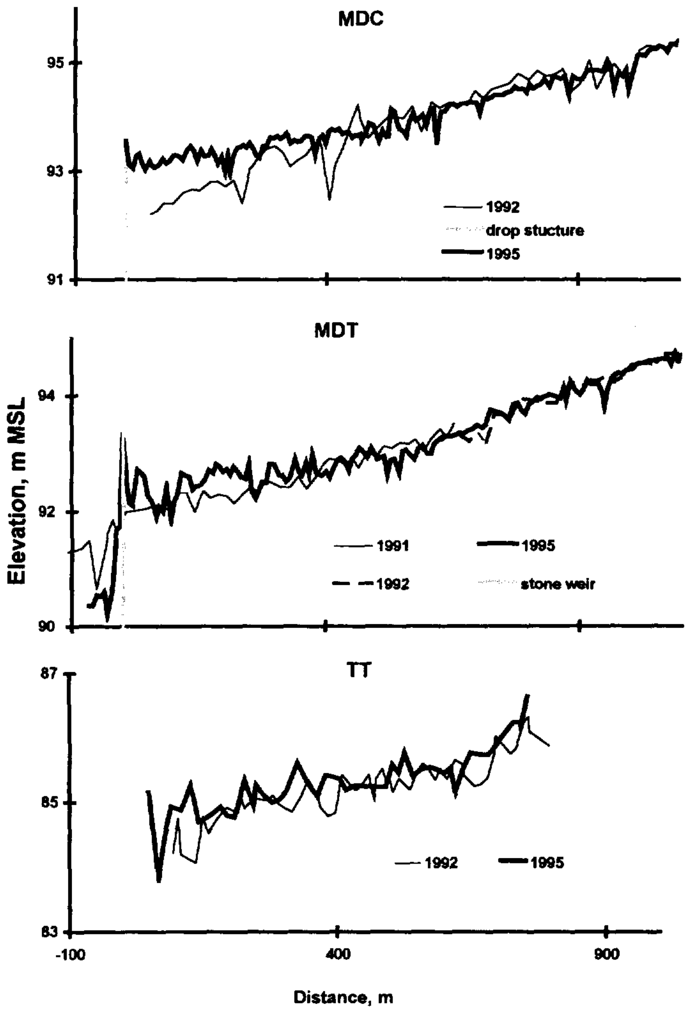

Fig. 3. Thalweg profiles before and after rehabilitation.

Table 1
Key physical habitat variables before and after construction of rehabilitation measures for Martin Dale Creek (MDC), Martin Dale Tributary (MDT) and Toby Tubby Creek (TT) in Northwest Mississippi, USA

Variable	MDC		MDT		TT	
	1991–92	1993–95	1991–92	1993–95	1991–92	1993–95
Mean discharge (l s^{-1}) (instantaneous Q measured during field data collection)	20	12	54	44	398	355
Median water depth (cm)	7	16	7	20	35	46
Median water width (m)	3.3	3.5	3.3	3.5	6.5	6.7
Median velocity (cm s^{-1})	6	2	10	3	16	9
Mean large woody debris density (m^2 km^{-2})	450	2900	0	4300	50 000	120 000
Mean no. of beaver dams km^{-1}	0.5	0.5	0.0	1.3	4.6	6.0

from 4 to 8% during the period of observation, probably due to the influence of beaver dams.

4.3. *Physical aquatic habitat*

Even though data were collected during lower discharges following construction, measured water depth and width were greater in all three streams during the 'post-construction' period (Table 1). Water depth, width and velocity measurements were not normally distributed, so differences in pre-and post-construction data sets were tested for significance using a Mann–Whitney Rank Sum Test (Glantz, 1992). Differences in medians were found to be significant in all cases ($p < 0.0001$ for depth and velocity and $p < 0.06$ for width). Following rehabilitation, median depth in MDC approximately doubled and median depth in MDT approximately tripled. However, water depths in both incised channels were extremely shallow relative to the non-incised reference site. As would be expected from the differences in discharge, median velocities followed the pattern TT > MDT > MDC. Habitat changes were especially evident when data collected at similar discharges were compared (Table 2). For example, mean depth increased by factors of 2.4 and 3.4 in MDC and MDT, respectively, but only by 1.2 in TT. Mean width increased by 2.2 and 1.2 in MDC and MDT, respectively, but was unchanged in TT. Changes in MDC and MDT were associated with rehabilitation structures, while beavers were the primary agent of change in TT (Table 1 and Table 2).

The observed changes in depth and velocity were related to pool formation. Pools were formed by three processes: backwater effects of the grade control weirs on MDC and MDT, local scour adjacent to stone toe on MDT and backwater effects of beaver dams on all streams, but particularly on TT. Following construction, pool habitat (arbitrarily defined as the percent of measurement points with depth > 30 cm and velocity < 10 cm s^{-1}) increased to more than 30% along both incised channels (Fig. 4). Most pool additions occurred immediately upstream of

Table 2
Mean (S.D.) values of water depth, width and velocity at 0.6 times depth on selected sampling dates with nearly identical discharges before and after rehabilitation constructional

	MDC		MD		TT	
	3 Oct 91	21 Sept 94	30 May 91	21 Sept 92	16 Jun 92	15 Jun 95
Discharge (l s^{-1})	10	9	62	60	468	423
Depth (cm)	12 (11)	29 (24)	8 (4)	27 (18)	40 (21)	47 (25)
Width (m)	2.2 (1.1)	4.9 (2.3)	3.6 (1.4)	4.3 (2.5)	6.6 (0.8)	6.6 (1.5)
Velocity (cm s^{-1})	9 (12)	1 (2)	20 (11)	5 (7)	17 (11)	13 (9)
No. of beaver dams[a]	0	1	0	1	0	5

[a] Beaver dams were 20–50 cm high and impacts were limited to reaches less than approximately 100 m.

the weirs and adjacent to stone toe. Pool habitat increased on MDC even prior to completion of construction due to backwater effects of a temporary diversion dam used during weir construction, a crude ford constructed by the landowner and beaver dams. However, pool habitat in MDC declined slightly during the last 2 years of observation, while MDT pools continued to increase. In MDC, pools created by the weir were gradually reduced by sedimentation. While sediment deposition also occurred for approximately 300 m upstream from the weir on MDT, depths adjacent to stone toe gradually increased slightly as the energy of higher flows was deflected from the banks to the bed. Pools along TT increased from near 10% to about 40% during the period of observation, reflecting the influence of higher levels of beaver activity and woody debris loading (Fig. 4 and Table 1).

The frequency distribution of bed types varied with current speed and antecedent hydrologic conditions throughout the period of observation but was always dominated by sand followed by clay (Table 3). Following rehabilitation, stone riprap

Table 3
Average (min–max) surficial bed type distributions, percent of sampled points.

Bed type	MDC		MDT		TT	
	1991–92	1993–95	1991–92	1993–95	1991–92	1993–95
Sand	57 (40–68)	72 (53–90)	57 (32–72)	58 (35–68)	63 (55–69)	60 (49–69)
Clay	40 (31–55)	23 (3–44)	30 (24–41)	28 (16–50)	1 (6–17)	23 (8–46)
Debris and detritus	2 (0–6)	2 (0–3)	2 (0–5)	5 (2–7)	25 (21–29)	17 (3–25)
Gravel	0 (0–0)	0 (0–1)	3 (0–8)	0 (0–1)	0 (0–0)	0 (0–0)
Submerged terrestrial vegetation or periphyton	1 (0–3)	3 (0–6)	4 (0–10)	2 (0–5)	1 (0–4)	1 (0–2)
Riprap	0 (0–0)	0 (0–1)	5 (0–9)	7 (3–10)	0 (0–0)	0 (0–0)
Total	100	100	100	100	100	100

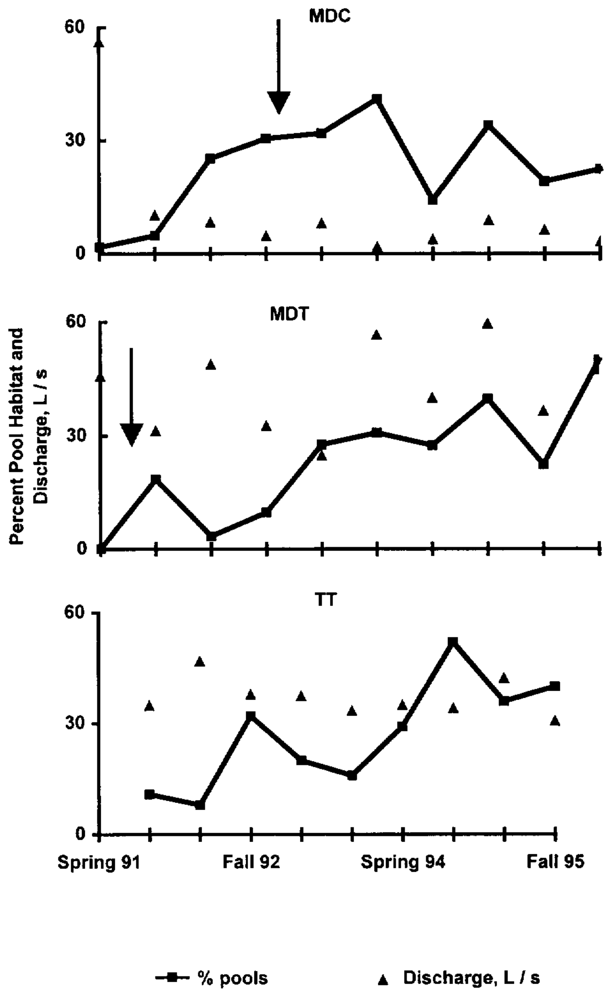

Fig. 4. Pool habitat versus time. Discharge values were measured concurrently with pool habitat. TT discharge is ten times the values shown. Vertical arrows indicate dates construction was completed.

and organic matter (debris and detritus) became slightly more common in the subaqueous bed along MDT. Along MDC, sand became more common and clay less common. TT substrates were dominated by sand throughout the study period. Debris was an order of magnitude more common on the TT bed than for the incised streams. Clay became more common along TT over the course of the study (increasing from 8% during year 2 to 32% in year 5), perhaps reflecting deposition patterns around beaver dams and woody debris.

Woody debris was scarce along both incised streams, but increased slightly following rehabilitation. Along MDC, the row of willow posts planted closest to the stream was quickly surrounded by water as the base flow channel migrated, and the posts furnished limited debris habitat. Fewer than 10% of posts survived 12 months due to dense, impermeable soils (Grissinger and Bowie, 1984) and competition by kudzu. Survival of willow sprouts on MDT was even lower than for posts along MDC, perhaps because the sprouts were planted during the summer. One to two beaver dams 50–75 cm high were found along both channels during periods of prolonged low flow. Some dams were made almost entirely of kudzu stems, attesting to the scarcity of wood! Shade canopy was nearly absent along MDC during the entire study, and declined slightly along MDT where trees were removed from the top of about 200 m of bankline prior to stone toe emplacement.

4.4. Fish community structure

Fish species richness (number of species per collection, where individuals captured from four 100 m reaches on a given date represents a collection) varied from 8 to 11 for MDT and from 5 to 11 for MDC and did not show any trend with time. A species list is provided in Appendix A. Differences in species richness between streams MDC and MDT and across sampling dates were not significant ($p > 0.63$). In accordance with its larger size and more pristine condition, TT was far more speciose than the incised streams, yielding 9–22 species per collection (mean = 17). Over the course of the entire study, streams MDC, MDT, and TT yielded 17, 18 and 48 species respectively. Perhaps more importantly, similar relationships held for number of species per 100 individuals captured (100 × number of species/number of individuals) as shown in Table 4. All of the 17 species found at MDC were also found in the other two streams, while only one species was unique to MDT. TT harbored 30 species not found in either MDT or MDC (Appendix A).

Rank-abundance graphs for the three streams highlighted differences in community structure (Fig. 5). Plots for MDC and MDT were nearly linear and approached a geometric series. The geometric series pattern is "found primarily in species-poor (and often harsh) environments or in the very early stages of succession. As

Table 4
Summary of fish collections.

	MDC		MDT		TT		
	1991–92	1993–95	1991–92	1993–95	1991–92	1993–95	1991–95
No. of individuals	3152	3419	2923	2286	855	2164	3019
No. of species	13	14	14	12	29	42	48
Biomass (kg)	5.7	16.5	7	13.5	51.5	16.4	17.4
CPUE (n min^{-1})	34.7	18.4	38.4	12.3	10.5	8.5	9.0
CPUE (g min^{-1})	63	89	92	73	631	65	52
No. of species 100 individuals^{-1}	0.41	0.41	0.48	0.52	3.39	1.94	1.59
Log series index	1.70	1.85	1.90	1.65	5.59	6.51	7.57

CPUE, catch per unit effort.

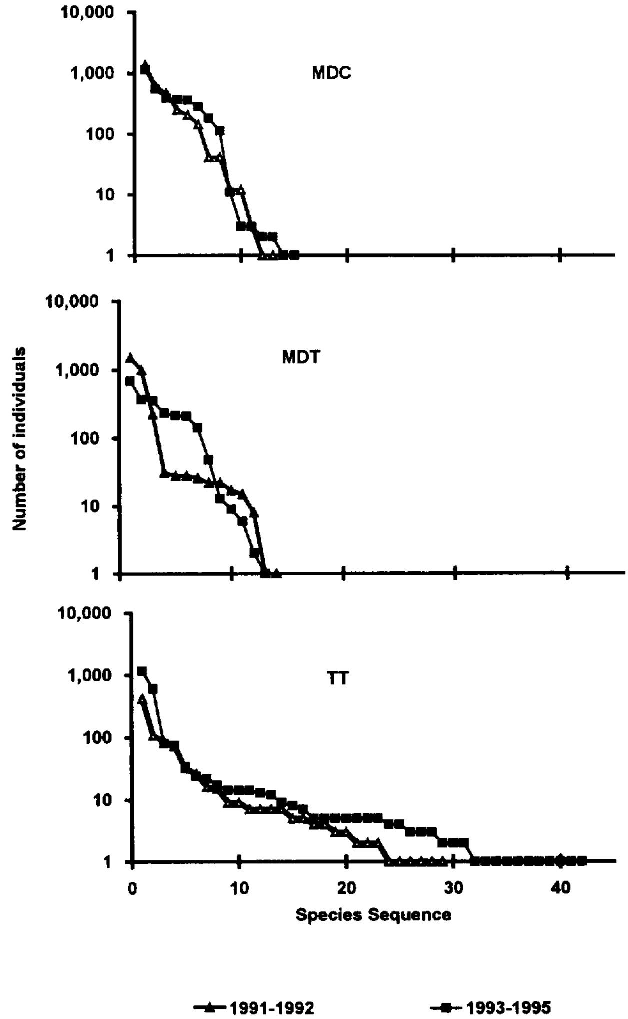

Fig. 5. Numerical abundance versus rank of abundance for fish species.

succession proceeds, or as conditions ameliorate, species abundance patterns grade into those of the log series" (Magurran, 1988). Following rehabilitation, fish species in MDT were more evenly distributed than before (Fig. 5). Species abundance patterns in TT exhibited high levels of richness but low levels of evenness. Of the 48 species found in TT, 14 were represented by one or two individuals and 31 were represented by eight or fewer individuals. The TT rank abundance plot (Fig. 5) was typical of a log series distribution-indicative of "a large, mature and varied natural community" (Magurran, 1988). The log series index, which is a robust index of species diversity (Magurran, 1988), was computed for each stream (Table 4). Higher levels of the index indicate higher levels of diversity and differences in the index are indicative of differences among sites. Following rehabilitation, the log series index increased slightly for MDC and TT and declined slightly for MDT. For both periods, the TT indices were about three times greater than those computed for the incised streams (Table 4).

Fish species composition was strikingly different in the reference and incised streams. TT harbored several uncommon species intolerant of physical and chemical habitat degradation, while MDC and MDT were dominated by tolerant species such as the cyprinids *Notropis rafinesquei* and *Semotilus atromaculatus* and the green sunfish, *Lepomis cyanellus*. These three species comprised 55% of all collections from MDC and MDT, but only 0.5% of collections from TT. About 44% of all individuals collected from TT were bluegill (*Lepomis macrochirus*) collected on just two of the fall sampling dates. Although the numbers of species in MDC and MDT were not affected by rehabilitation, trends were observed in relative abundance at the family level. Cyprinids, principally the Yazoo shiner (*Notropis rafinesquei*) which prefers shallow, sandy habitats (Suttkus, 1991), dominated early collections, but later declined. At MDC and MDT, this species comprised 47 and 70%, respectively, of the catch by number in 1991 but only 12 and 5% in 1995. Pool-dwelling catostomids and centrarchids increased in relative abundance as run-dwelling cyprinids declined, shifting composition patterns toward that of TT (Table 5 and Fig. 6). These changes were more pronounced and persistent for MDT than MDC.

4.5. Fish catch

Catch per unit effort (CPUE) for the incised streams MDC and MDT declined from an average of 57 fish $\min^{-1}$ the first year to 14 fish $\min^{-1}$ the fifth year, reflecting a shift in community structure away from large numbers of cyprinids. The variance in CPUE between these two streams was not significant, but variance with time was significant ($p = 0.003$, two-way ANOVA). TT CPUE varied from 3 to 27 fish $\min^{-1}$ without any trend. Although TT numbers per unit effort were lower than for MDC or MDT, individuals were larger as evidenced by the higher values for biomass (Table 4).

For MDC and MDT, biomass ranged from 0.4 to 3.9 kg per collection (collection = all individuals captured from a stream on a given date) and averaged about 2 kg. Biomass per unit effort did not vary significantly between MDC and

Table 5
Pearson product moment correlation coefficients (p values) between fish collections from incised streams (MDC and MDT) and concurrent collections from non-incised reference stream (TT)

Period	MDC with TT	MDT with TT	MDC with MDT
1991–92	−0.06 (0.90)	−0.19 (0.69)	0.93 (0.0007)
1993–95	0.28 (0.41)	0.54 (0.14)	0.92 (0.00006)

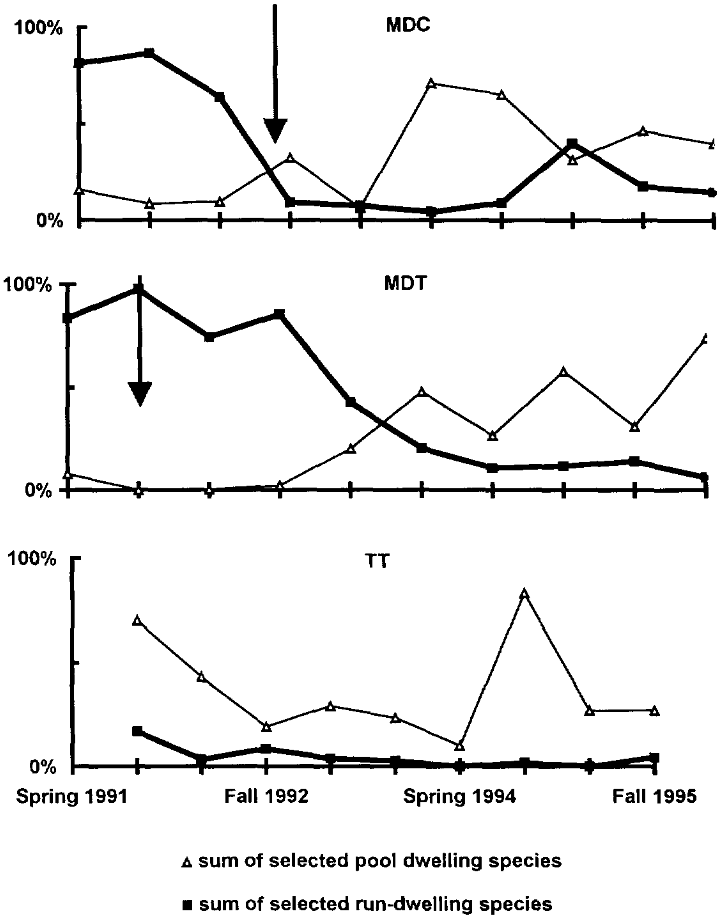

Fig. 6. Relative abundance of selected fish species versus time. Pool species are bluegill (*L. macrochirus*), green sunfish (*L. cyanellus*), creek chubsucker (*K. oblongus*), and yellow bullhead (*A. natalis*). Run species are Yazoo shiner (*N. rafinesquei*), blacktail shiner (*C. venusta*), and bluntface shiner (*C. camura*). Vertical arrows indicate when construction was completed.

MDT or through time ($p > 0.22$, two-way ANOVA). TT supported higher levels of biomass, ranging from 0.9 to 35.6 kg per collection and averaging 7.5 kg. The highest level (35.6 kg) was for the first collection, which was a fall sample following an extremely wet spring with prolonged overbank flooding. TT biomass per unit effort gradually declined over the course of the study (r^2 with time = 0.49, $p = 0.03$).

4.6. Fish size

Smaller fishes dominated all MDC and MDT collections, with no individual longer than 27 cm or weighing more than 140 g. Plots of length frequency distributions of five selected fish species well-represented in MDC and MDT collections (*E. oblongus*, *L. macrochirus*, *L. cyanellus*, *S. atromaculatus*, and *A. natalis*) were constructed for MDC and MDT for each sampling date (Fig. 7). Plots from MDT revealed stronger patterns of recruitment following rehabilitation, but patterns for MDC were erratic. Following rehabilitation, individuals longer than 10 cm comprised a larger percentage of the catch from MDT for all five species, but a smaller or unchanged percentage of the MDC catch (Table 6). Since length data were not normally distributed, distributions before and after rehabilitation were compared using the Mann–Whitney rank sum test. Differences in median lengths were statistically significant ($p < 0.03$) for three of the selected species from MDC and for one at MDT (Table 6). Median lengths for MDT collections were larger following rehabilitation, but four of the five MDC medians were smaller after rehabilitation. Only two of the five selected species were well-represented in the TT collections (Appendix A), but members of both included large individuals relative to the incised channel collections: median lengths for *E. oblongus* and *L.*

Table 6
Effect of rehabilitation on total numbers, median length and numbers of large individuals of selected fish species

Family	Taxon		MDC		MDT	
			1991–92	1993–95	1991–92	1993–95
Catostomidae	*Erimyzon oblongus*	No. per year	6	173	1.1	117
		Median length (cm)	8.9*	7.8*	7.3	7.5
		>10 cm (%)	25	25	14	32
Centrarchidae	*Lepomis macrochirus*	No. per year	2.1	124	1.1	122
		Median length (cm)	5.7	5.2	5.2*	7.5*
		>10 cm (%)	10	0	9	27
	Lepomis cyanellus	No. per year	126	121	1.6	48
		Median length (cm)	5.5*	6.2*	7.4	8.0
		>10 cm (%)	13	9	16	23
Cyprinidae	*Semotilus atromaculatus*	No. per year	104	232	112	230
		Median length (cm)	5.7*	2.4*	6.0	7.0
		>10 cm (%)	10	7	14	17
Ictaluridae	*Ameiurus natalis*	No. per year	20	6.1	0	1.6
		Median length (cm)	8.4	7.3	—	13.5
		>10 cm (%)	38	27	0	77

Length distributions were compared using the Mann–Whitney rank sum test.
* Medians are significantly different ($p<0.03$).

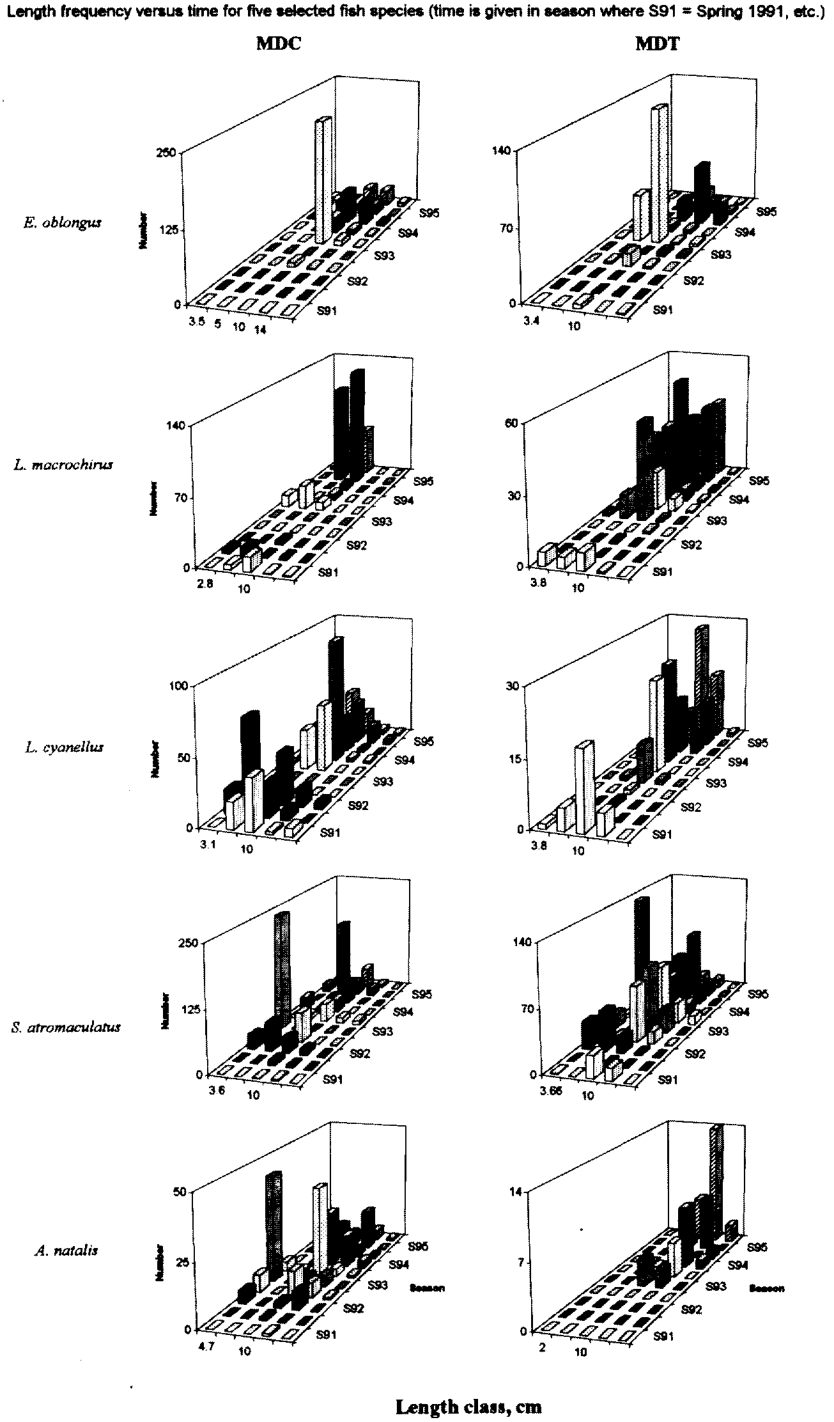

Fig. 7. Length frequency for five selected fish species versus time for streams MDC and MDT. The vertical axis is the number of individuals, while the horizontal axes are fish length in cm and date (e.g. S91 = Spring 1991).

macrochirus from TT during the entire study were 6.1 cm ($n = 1566$) and 14.0 cm ($n = 13$), respectively.

5. Discussion

Prior to disturbance, streams MDT and MDC were likely sinuous, shallow channels with abundant woody debris and riparian vegetation. At the reach scale, the kinetic energy of flowing water was dissipated rather uniformly along the length of each channel by the effects of bends, woody debris and rough and irregular channel boundaries. Wake zones and eddies created by these features also provided pool habitats and cover essential for communities containing fewer but larger fishes of certain warmwater species (Schlosser, 1982, 1987). This type of physical structure is typical of undisturbed fluvial systems and is evident along TT. Straightening (channelization) of MDC and MDT, coupled with base level lowering, increased bed slope and stream power per unit bed area.

Rehabilitation strategies for MDC and MDT focused on reducing bed slope and lowering unit stream power by removal of energy at a discrete point, a weir.

In spite of the bias our data analysis approach created against MDT response, the results indicated that the MDT rehabilitation project led to stronger trends in pool habitat availability and fish size toward the TT reference condition than for MDC (Tables 6 and 7). This may reflect the extent to which predisturbance physical conditions (pool habitats and cover) were recreated and then maintained by the slight bends and the 700 m of stone toe bank protection. Although the stone toe is by no means a natural element in this landscape, it does provide cover, some scour hole development, and substrate for macroinvertebrates in a fashion similar to naturally-occurring structural features. Sand bed channels tend to deepen adjacent to stone toe placed on a concave bank. This 'resisted lateral scour' (White, 1991) is similar to the condition created by a heavily vegetated bank in a less disturbed stream. In natural streams, resisted lateral scour often leads to undercut banks, which are prime habitat for fishes. Unfortunately, the stone toe precludes development of undercut banks.

Stilling basins below grade control structures in incised, warmwater streams provide aquatic habitats superior in some respects to naturally-occurring pools (Cooper and Knight, 1987) and facilitate initial ecological recovery in these badly damaged systems (Shields and Hoover, 1991). However, current design practice calls for relatively few, large structures per unit channel length, limiting their positive effect on system-wide recovery. For example, plans for stabilizing 5910 km^2 of incising watersheds in northwest Mississippi include only 148 drop structures (Shields et al., 1995f). Previous restoration studies of warmwater streams damaged by channel incision have illustrated the positive effects of distributing structures along the length of the channel (Shields et al., 1996, 1995a,b, 1993a,b). Results of these efforts are summarized in Table 7, which shows that restoration projects on streams H and G produced greater increases in species richness, fish size, water depth (G only) and biomass catch per unit of effort (H only). We hypothesize that this was due to a combination of factors:

Table 7
Results of rehabilitation of 1 km reaches of incised, warmwater streams in Northwest Mississippi

	Stream			
	H	G	MDC	MDT
Reference	(Shields et al., 1995a, 1996)	(Shields et al., 1995b, 1996)	Present paper	Present paper
Watershed (km^2)	91	21	12	14
Rehabilitation measures	16 stone spur dikes, 3400 willow posts[a]	18 stone weirs, 1400 willow posts[a]	1 drop structure, 4300 willow posts	1 stone weir, stone toe protection, 3000 willow sprouts
Physical response increase				
Pool habitat[b] (%)	2–7	25–74	5–34	0–40
Mean depth at baseflow (cm)	14 17	18 48	12–29	8–27
Biological (fish) response				
Catch per unit effort (n min^{-1})	Increased from 10 to 15	Decreased from 40 to 14	Decreased from 35 to 18	Decreased from 38 to 12
Catch per unit effort (kg/100 m)	Increased from 0.2 to 1.5	Decreased from 1.3 to 1.0	Increased from 0.4 to 0.7	Increased from 0.4 to 0.6
Mean no. of species per collection	Increased from 11 to 9	Increased from 15 to 18[c]	Unchanged at 9	Unchanged at 9
Family composition by no.[d] (%)	Cyprinids declined from 60 to 49	Cyprinids declined from 69 to 53	Cyprinids declined from 84 to 48	Cyprinids declined from 95 to 50
Fish size	Median length (all species) increased from 3.6 to 5.5 cm	Median length of five selected species increased	Median length of four of five selected species decreased	Median length of four selected species increased

[a] Study areas were immediately upstream from low drop structures placed prior to rehabilitation.
[b] Arbitrarily defined as all areas with depth greater than 20 cm and velocity less than 10 cm s^{-1} for H and G, depth greater than 30 cm and velocity less than 10 cm s^{-1} for MDC and MDT.
[c] Reflects supplementation of electroshocking collections with a single rotenone collection following restoration due to declining electrofishing efficiency with increasing water depth.
[d] Published results for H and G supplemented with more recent unpublished data from our files.

1. rehabilitation efforts on MDC and MDT were primarily standard channel stabilization practices applied without consideration of habitat goals. The primary habitat feature, planting willow posts along MDC, was limited to 500 m of the 1 km study reach and was unsuccessful;
2. projects at streams H and G incorporated numerous spurs and small weirs along the treated reach. Previous studies have highlighted the superiority of discrete structures like spur dikes over continuous bank protection (stone toe) for aquatic habitat rehabilitation (Shields et al., 1995c,d);
3. initial habitat conditions at MDC and MDT were worse than for the other sites, as was evidenced by the low fish species richness and the dominance of Yazoo shiners (Shields et al., 1995e);
4. the study reaches at MDC and MDT are more distant from habitats that could provide colonizing organisms than at H. In addition, weirs may be barriers to upstream migration. Weirs were also present at the downstream ends of study reaches at H and G, but the weir on H was submerged at higher flows.

The development of pool habitats along MDC and MDT is a positive sign and attendant shifts in fish species composition may presage more positive biological developments. On the other hand, more than half of the increase in pool habitat occurred immediately upstream of the weirs, and these pools are rapidly being filled with sediment. Long term recovery of the stream corridor ecosystem is hindered by the isolation of the stream from the floodplain and by kudzu competition with native riparian species.

6. Conclusion

Recovery of habitat resources in deeply incised low-order warmwater streams draining agricultural watersheds is likely to be slow and minimal without a more aggressive approach to addressing environmental goals in channel stabilization design. Designs which feature distribution of structure along a reach rather than concentration of effort in one or only a few large structures are likely to be more effective. Furthermore, smaller weirs are less likely to be obstacles to upstream migration of colonists. Additional research is needed to develop cost-effective techniques for restoring native woody vegetation on incised channel banks infested with exotic species like kudzu.

Acknowledgements

Surveys were performed by Continental Engineering, Leggitt Land Surveying Company, and Castles and Associates. Kyle Waide, Monica Young, Sam Testa, Bill Westling, Rick Fauteux, Stan Crider, John Endom, Mary Evelyn Barnes, Cliff Dew, Mark Weeden, Shawn Yates, Jennifer Bowen, Belinda Garraway, Peter Smiley, Terry Welch, Michelle Malott, Leanne Hughes, Pat McCoy, Herbert Shaw and Martin Doyle assisted with field data collection and analysis. Frank Hudson, Jasper Lummus, and numerous other personnel of the Vicksburg District of the US Army Corps of Engineers assisted with planning, and design and construction of the rehabilitation project. Willow post planting on Stream MDC was directed by Steve Wilson, Larry Pride and Henry Simmons of the Natural Resources Conservation Service. Bruce Rhoads, Lou Toth, Andrew Simon and Brian Todd read a draft of this paper and made many helpful suggestions.

Appendix A. Fish collected from three northwest Mississippi streams, 1991–1995

Family	Taxon	MDC		MDT		TT		
		1991–92	1993–95	1991–92	1993–95	1991–92	1993–95	All
Aphredoderus	*Aphredoderus ayanus*					1	1	2
Atherinidae	*Labidesthes sicculus*					4	5	9
Catostomidae	*Minytrema melanops*					7	14	21
	Moxostoma poecilurum					1	1	
	Erimyzon oblongus	12	549	22	352	1	12	13
Centrarchidae	*Micropterus salmoides*		1			26	14	40
	Lepomis macrochirus	41	372	22	366	417	1149	1566
	Lepomis microlophus					2	4	6
	Lepomis gulosus					7	24	31
	Lepomis megalotis		3				8	8
	Pomoxis nigromaculatus					7		7
	Micropterus punctulatus	12	2		2	88	34	122
	Lepomis humilis						5	5
	Lepomis cyanellus	251	362	31	143		1	1
	Lepomis marginatus						7	7
	Lepomis punctatus					9	13	22
Clupeidae	*Dorosoma cepedianum*					2	1	3
Cyprinidae	*Cyprinella lutrensis*		2	26	6			

Family	Taxon	MDC		MDT		TT		
		1991–92	1993–95	1991–92	1993–95	1991–92	1993–95	All
	Semotilus atromaculatus	206	1138	224	689			
	Cyprinus carpio					3	1	4
	Cyprinella venusta	606	112			107	5	112
	Campostoma anomalum					1		1
	Hybognathus nuchalis						1	1
	Opsopoeodus emiliae						1	1
	Notropis atherinoides			17		72	603	675
	Notropis texanus						5	5
	Lythrurus umbratilis			8			5	5
	Luxilus chrysocephalus						4	4
	Notemigonus crysoleucas				13	1	2	3
	Pimephales notatus	1				9	1	10
	Cyprinella camura	473	11	996	209	15	22	37
	Notropis rafinesquei	1362	393	1504	215		14	14
Esocidae	*Esox niger*						1	1
	Esox americanus						2	2
Fundulidae	*Fundulus notalus*		3		9			
	Fundulus olivaceus	143	287	28	234	16	80	96
Ictaluridae	*Ameiurus melas*	3		28				
	Icialurus punctatus	1				3	1	4
	Ameiurus natalis	41	184		48	3	3	
	Noturus phaeus			1		7	9	16
	Noturus					1		1
Lepisosteidae	*Lepisosteus oculatus*					5		5
Percidae	*Etheostoma parvipinne*			1				
	Etheostoma chlorosomum					1		1
	Etheostoma nigrum						3	3
	Percina sciera			15		32	75	107

Family	Taxon	MDC		MDT		TT		
		1991–92	1993–95	1991–92	1993–95	1991–92	1993–95	All
	Etheostoma histrio					4	2	6
	Etheostoma whipplei						17	17
	Etheostoma proeliare					5		5
	Etheostoma sp						1	1
Petromyzontidae	*Ichthyomyzon gagei*						5	5
Poeciliidae	*Gambusia affinis*						3	3
Sciaenidae	*Aplodinotus grunniens*					2	5	7

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